ERDC/GSL TR-09-20

Geotechnical and Structures Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

In Situ Evaluation of Unsurfaced Portland Cement-Stabilized Soil Airfields

Jonathon R. Griffin and Jeb S. Tingle

July 2009

Approved for public release; distribution is unlimited.

ERDC/GSL TR-09-20
July 2009

In Situ Evaluation of Unsurfaced Portland Cement-Stabilized Soil Airfields

Jonathon R. Griffin and Jeb S. Tingle

Geotechnical and Structures Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Prepared for Headquarters, Air Force Civil Engineer Support Agency
139 Barnes Avenue, Suite 1
Tyndall Air Force Base, FL 32403-5319

Abstract: The U.S. Army Engineer Research and Development Center was tasked to develop a method for the in situ evaluation of unsurfaced Portland cement-stabilized soil airfields. The ability of portable in situ strength and stiffness measuring devices to determine the material properties of stabilized soils was investigated using the Clegg hammer, dynamic cone penetrometer, soil stiffness gauge, portable falling-weight deflectometer, and portable seismic property analyzer. Regression and correlation analyses were performed to develop relationships between the in situ test device measurements and the unconfined compressive strength, modulus of rupture, repeated-load elastic modulus, and falling-weight deflectometer backcalculated elastic modulus of representative materials. Relationships proposed in previous studies were found ineffective, and a precise relationship for the determination of cement-stabilized soil material properties was not discovered. As a result of this study, it has been determined that further research is required for the development of an accurate cement-stabilized soil performance model.

Contents

Figures and Tables

Figures

Tables

Preface

The project described in this report was sponsored by Headquarters, Air Force Civil Engineer Support Agency, Tyndall Air Force Base, FL.

This publication was prepared by personnel of the U.S. Army Engineer Research and Development Center (ERDC), Geotechnical and Structures Laboratory (GSL), Vicksburg, MS. The findings and recommendations presented in this report are based upon a series of field tests conducted at Camp Joseph T. Robinson, AR and Fort Polk, LA in June 2007, in addition to field and laboratory tests conducted at the ERDC from July 2007 to April 2008.

The research team consisted of Jonathon R. Griffin, Jeb S. Tingle, Terry V. Jobe, and Thomas J. Beasley, Airfields and Pavements Branch (APB), GSL. Griffin and Tingle prepared this publication under the supervision of Dr. Gary L. Anderton, Chief, APB; Dr. Larry N. Lynch, Chief, Engineering Systems and Materials Division; Dr. William P. Grogan, Deputy Director, GSL; and Dr. David W. Pittman, Director, GSL.

COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Recommended changes for improving this publication in content and/or format should be submitted on DA Form 2028 (Recommended Changes to Publications and Blank Forms) and forwarded to Headquarters, U.S. Army Corps of Engineers, ATTN: CECW-EW, Kingman Building, Room 321, 7701 Telegraph Road, Alexandria, VA 22315.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
square inches	6.4516 E-04	square meters

1 Introduction

The U.S. Army Engineer Research and Development Center (ERDC) was tasked to develop a method for the in situ evaluation of unsurfaced Portland cement-stabilized soil airfields. Unsurfaced stabilized soil airfields are commonly used by the Department of Defense (DoD) as alternative launch and recovery surfaces (ALRS) and also as contingency training facilities. Stabilized soil surfacing can be a cost-effective alternative to both Portland cement concrete and asphalt concrete surfaces, while providing increased bearing capacity and durability compared with untreated aggregate surfaces.

Objective

Guidance for the in situ evaluation of unsurfaced stabilized soil pavement layers does not currently exist. The objectives of this project are to

- evaluate the feasibility of using in situ test devices to characterize the stabilized surface material,
- develop correlations between in situ test measurements and standard laboratory test methods,
- evaluate the ability to use in situ test devices to generate input values for existing pavement evaluation software,
- determine the ability of existing pavement evaluation software to predict the performance of Portland cement-stabilized soil pavement layers,
- propose a method for the in situ evaluation of unsurfaced stabilized soil airfields.

The fulfillment of these objectives will lead to the development of a rapid method for assessing an unsurfaced stabilized soil airfield and reliably predicting the remaining operational capacity.

Scope

The objectives of this project will be addressed by

- evaluating existing unsurfaced cement-stabilized soil airfields using portable strength and stiffness measuring tools,

- conducting laboratory testing of samples recovered from the airfields to determine the material properties using standard methods,
- conducting regression analyses to determine the existence of relationships between in situ measurements and laboratory test values for the materials,
- determining the feasibility of using in situ test device measurements as required inputs for pavement evaluation software,
- constructing a test section to verify the approach outlined in the previous steps,
- developing an analytical approach for an unsurfaced stabilized soil airfield evaluation procedure.

Outline of chapters

Chapter 2 provides background information concerning soil stabilization with Portland cement, descriptions of potential devices for in situ characterization of stabilized materials, an outline of the standard test methods employed, and an introduction to the pavement evaluation software used in this study. Chapter 3 describes the field data collection. Chapter 4 presents the results of the study, including descriptions of the regression analyses and pavement evaluation procedure. Chapter 5 describes the verification of the models and critical findings. Chapter 6 presents the pertinent conclusions and recommendations.

2 Background

Soil stabilization with Portland cement

The stabilization of in situ soils that do not possess the required properties for a given engineering application with Portland cement can be an effective and economical means of improving the quality of the native material. Civil engineers commonly employ this proven remediation technique in lieu of more costly alternatives, such as removal and replacement of the marginal soil. However, despite the widespread use of cement stabilization within both the civilian and military pavement communities, no method currently exists for determining the performance capacity of cement-stabilized layers. A method is needed to verify if new construction will provide the operational capacity specified in the design and to determine the remaining performance capacity of existing stabilized soil layers.

Soil stabilization refers to the process by which the properties of natural soils are improved by the addition of supplementary materials. The stabilization of soils is accomplished by either mechanical or additive stabilization. Technical Manual (TM) 5-822-14 (Joint Departments 1994) defines mechanical stabilization as the process of modifying a soil to meet a specific gradation by blending with another soil, while additive stabilization is achieved by mixing additional substances into the parent soil. Commonly used additive materials include Portland cement, lime, fly ash, asphalt cement, polymers, and fibers. The objective of stabilization is to improve a specific property or properties of a soil to make it more suitable for a particular engineering application. Properties of soils that can be improved through the process of stabilization include increased strength, durability, and cohesion; reduced swelling potential; and improvements in gradation (TM 5-822-14). Common applications of soil stabilization include pipe bedding, retaining walls, slope protection, control of expansive soils, and pavement layers for airfields, roadways, and parking lots.

Stabilization with Portland cement is one of the most widely used and most economical methods of soil stabilization (Wang 1968). Cement-stabilized soil layers are semirigid, improved material layers that provide additional bearing capacity and durability beyond that provided by the existing soil layers. Portland cement, when used as a stabilizing material, is blended with a soil to increase the percentage of fines, increase the

interparticle friction within the soil mass, and reduce the moisture susceptibility of the parent material. Stabilization with Portland cement can be used with a variety of soils but is most effective with well-graded, low-plasticity soils. Typical cement content ranges from 5% to 11% by weight and is determined by the soil type, environmental conditions, and the intended use of the soil layer (TM 2-822-14). The performance of Portland cement-stabilized soils is affected by a number of factors, including the cement content, parent soil mineralogy and gradation, construction practices used, and curing method employed (Mitchell et al. 1974).

Material characterization

The development of a damage model for analyzing stabilized soil layers was the focus of a study by Heymsfield et al. (2007). The researchers sought to model the elastoplastic behavior of stabilized soils using a numerical finite element model that incorporated Valanis' damage model. The damage model was initially developed to determine failure in brittle and semibrittle materials but was modified in Heymsfield's research to model plastic behavior. The materials examined in the study were an SM soil stabilized with 4% Portland cement, 4% Portland cement and 1.5-in. polypropylene fibers, and 6% Portland cement. As a result of the investigation, the researchers determined that material strength and stiffness as determined using unconfined compression load and unconfined repeated-load tests were required to model the mechanical behavior of stabilized materials.

Determination of the material properties of strength and stiffness generally requires sampling and returning stabilized material to the laboratory for testing. The transportation and testing of samples is time consuming and cost ineffective. Additionally, it is often not possible to obtain intact cores from low-strength, cement-stabilized materials (Okamoto et al. 1991). Therefore, the in situ measurement of these properties with minimal damage to the pavement structure could provide a rapid and economical means for characterizing the material. However, it should be noted that in situ testing can be used to evaluate the properties only at the time of testing, because of the high sensitivity of stabilized soils to variations in time and environmental conditions (Wang 1968).

The in situ characterization of Portland cement-stabilized soil pavement layers using the Clegg hammer, dynamic cone penetrometer (DCP), soil

stiffness gauge (SSG), portable falling-weight deflectometer (PFWD), and portable seismic property analyzer (PSPA) was examined in this effort.

Clegg hammer

The Clegg hammer is widely used for monitoring the level of compaction, surface stiffness, and impact characteristics of soils. The Clegg hammer is composed of a steel guide tube and an instrumented hammer. The end of the hammer is equipped with an accelerometer that measures deceleration as it impacts a surface after falling a fixed distance inside the rigid guide tube.

The Clegg hammer is available with hammer masses of 1, 5, 10, and 45 lbm (0.5, 2.25, 4.5, and 20.0 kg). The standard Clegg hammer (10 lbm) is depicted in Figure 1. Measurements are reported in terms of the Clegg impact value (CIV), which is equivalent to 10 times the acceleration caused by Earth's gravity (1 CIV = 10 G). Strength testing can be rapidly conducted on both soft and hard surfaces using the hammer. Testing of very stiff materials, greater than 100 CIV, should be avoided as extensive use on extremely hard surfaces has been shown to damage the unit (Freeman et al. 2008).

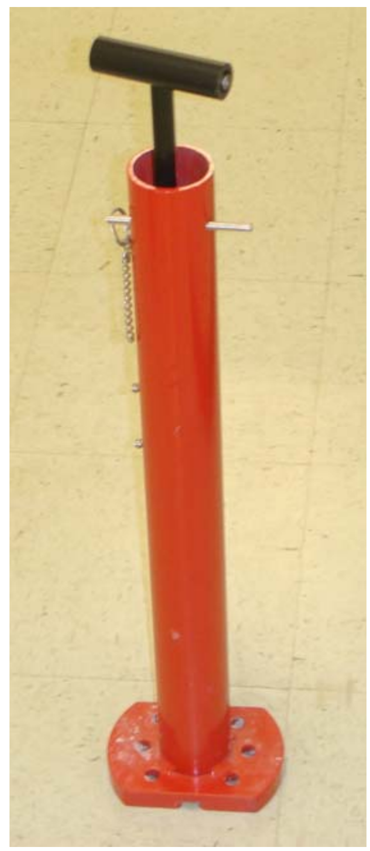

Figure 1. Standard Clegg hammer.

The feasibility of using the Clegg hammer to conduct in situ material characterization of stabilized soils has been examined in previous studies by Freeman et al. (2008) and Guthrie and Reese (2008). As part of a project to determine the best approach to quality assurance on contingency airfields with limited resources, Freeman et al. (2008) investigated both the ability of portable test devices to measure the stiffness of stabilized soil surfaces and the applicability of relationships between measurements with the devices and the in situ strength of the material. The CIV measured with a standard Clegg hammer was correlated to the unconfined compressive strength (UCS) of untreated SM soils and SM

soils stabilized with 4% by weight of Portland cement with a coefficient of determination of 0.99.

The Clegg hammer has also been used to monitor the increase in stiffness of stabilized materials with increasing cure time. Guthrie and Reese (2008) investigated the ability of a heavy (45-lbm) Clegg hammer to determine the rutting susceptibility of stabilized soils under early trafficking. In the study, an SW-SM soil stabilized with 2% by weight of Portland cement was tested using the heavy Clegg hammer and subjected to simulated traffic. As a result of the study, it was concluded that the heavy Clegg hammer was capable of detecting the increase in stiffness as the material cured. However, no direct correlation between CIV and resistance to rutting could be developed.

Dynamic cone penetrometer

The DCP is a tool capable of rapidly determining the resistance to penetration of a material. This device is used extensively in both military and civilian applications to determine the in situ strength of soil layers.

The penetrometer is intended for use in horizontal construction applications, including fine and coarse grained soils, granular construction materials, and weak stabilized or modified materials. Materials underlying a bound surface layer can be tested by first drilling or coring an access hole. The typical apparatus is composed of a handle, two rods, either a 10.1 lbm (4.58 kg) or 17.6 lbm (7.98 kg) hammer, an anvil, and a conical tip. The DCP is shown in Figure 2. The data output of the DCP is the DCP index. The DCP index is a measure of the penetration rate, or the depth of penetration, of the conical tip with each blow of the hammer.

In a study to determine the feasibility of using portable test devices to characterize stabilized materials, the DCP was used to evaluate stabilized soils and the results of the testing correlated to standard test methods. The investigated materials included cement-stabilized, lime-stabilized, granular, and clayey soils. The DCP was correlated with the plate loading test (PLT), falling weight deflectometer (FWD), and California bearing ratio (CBR) standard test methods. The result of the regression analysis of the relationships of DCP testing and the standard PLT, FWD, and CBR test methods yielded coefficients of determination of 0.91, 0.94, and 0.93, respectively (Nazzal 2003).

The DCP was also used in developing correlations between the DCP test method and the strength properties of Portland cement and lime-treated subgrades.

Enayatpour et al. (2007) tested an untreated control soil and the same parent soil—treated with two dosages of Portland cement (5% and 10% by weight) and also with two dosages of lime (4% and 8% by weight). Correlations were developed to predict the UCS using stabilizer content (percent), curing time (days), and DCP index (in centimeters per blow). The coefficients of determination for the Portland cement stabilization and lime stabilization relationships were 0.97 and 0.91, respectively.

Figure 2. Dynamic cone penetrometer.

Soil stiffness gauge

The SSG is a portable device providing a rapid determination of elastic modulus for a soil. The SSG is a hardened disk measuring 11 in. in diameter and 10 in. high. The device uses a steel ring with a 4.5-in. diameter on the underside of the device and in contact with the surface to impart small displacements to the soil to determine the impedance, stress, and resulting surface velocity, from which stiffness is derived. Testing with the SSG is shown in Figure 3.

The SSG is intended for use on soils with in-place stiffness in the range of 17,130–399,700 lbf/in. (3–70 MN/m) and elastic modulus in the range 3,800–88,470 psi (26.2–610 MPa). The output of the SSG is stiffness and, with known Poisson's ratio, elastic modulus.

The SSG has been used to estimate the in situ stiffness of stabilized soils in previous studies. In an investigation of the feasibility of using portable devices to measure stiffness, the SSG was successfully correlated to FWD, PLT, and CBR test methods for materials with stiffness less than 131,300 lbf/in. The coefficients of determination for the relationships are 0.81, 0.87, and 0.84, respectively (Nazzal 2003).

Figure 3. Testing stabilized surface with SSG.

In a study to examine the engineering behavior of stabilized soils, the SSG was used to determine the stiffness of lime, fly ash, Portland cement, and enzymatic stabilized soils. In this testing, the SSG was shown to be able to measure changes in stiffness and modulus in stabilized materials (Parsons and Milburn 2003). Additionally, a moisture-stiffness relationship was recognized for stabilized materials, and defining that relationship can be accomplished using the SSG (Parsons and Milburn 2003).

Portable falling-weight deflectometer

The PFWD is a portable lightweight configuration of the traditional FWD. The instrument provides an in situ measurement of stiffness and bearing capacity for soil layers. A falling mass is used to impact buffers, which transmit a measured impulse load to a circular loading plate in contact with the surface. The resulting deflection at the center of the plate is measured using a geophone. The magnitude of the mass can be increased in 11.0-lbm (5.00-kg) increments from 22.0 lbm (10.0 kg) to 44.0 lbm (20.0 kg). Interchangeable loading plates are also available for the PFWD in diameters of 3.94 in. (100 mm), 7.87 in. (200 mm), and 11.81 in. (300 mm). Additional geophones can be added to the system to obtain a deflection basin showing surface deflection at fixed distances outward from the load application. An example of a PFWD is shown in Figure 4.

Figure 4. Testing stabilized surface using PFWD.

The device is intended for use on horizontal construction surfaces. The output of the device is measured deflection, and the elastic modulus can be determined with a known material Poisson's ratio.

The PFWD has been successfully used to characterize stabilized soils in a study to determine the feasibility of measuring in situ stiffness using portable devices. A regression analysis was performed to develop correlations between PFWD testing and the PLT, FWD, and CBR standard test methods (Nazzal 2003). The testing was conducted on three highway pavement sections in addition to nine test sections. The materials investigated included both Portland cement and lime-stabilized soils. The PFWD was correlated to the FWD, PLT, and CBR test methods with coefficients of determination of 0.94, 0.92, and 0.83, respectively (Nazzal 2003), indicating that the PFWD can be used in lieu of traditional test methods to characterize stabilized soils.

Portable seismic property analyzer

The PSPA is a portable seismic test device with the ability to nondestructively evaluate concrete, asphalt, and prepared subgrade materials. The device consists of an electronics box, extension rods, a wave generation source, and two receivers. The system is controlled by a laptop computer that also records the data. Testing of a stabilized surface with the PSPA is shown in Figure 5. The PSPA generates ultrasonic surface waves (USW), the speeds of which are measured by the two receivers. Along with the Poisson's ratio and the mass density of the tested material, the velocity of the USW is used to calculate the Young's modulus. The output of the PSPA is elastic modulus.

Figure 5. Testing stabilized surface with the PSPA.

The PSPA has not been documented for the evaluation of stabilized soils. However, studies have shown that seismic testing is an effective alternative to traditional modulus determination methods for stabilized materials. The current methods for determining the modulus of stabilized materials are either by repeated-load testing or backcalculating modulus

values using deflection data collected using a FWD. Testing was conducted on a variety of stabilized materials, and seismic modulus testing was shown to be an effective method for predicting modulus with lower equipment cost and reduced testing time compared with the repeated-load and FWD test methods (Hilbrich and Scullion 2007). The developed correlation between seismic and resilient modulus had a coefficient of determination of 0.93 (Hilbrich and Scullion 2007).

The use of the PSPA to evaluate rigid and flexible pavement surfaces has been documented in an investigation into the feasibility of using the PSPA to determine the elastic modulus and flexural strength of Portland cement and asphalt concretes (Bell 2006b). Bell (2006b) determined the PSPA was able to provide a reliable measure of the elastic modulus, and a correlation was developed for the relationship between PSPA modulus and flexural strength with a coefficient of determination of 0.53.

Summary

Based on a review of currently available literature, portable test devices can be used to measure the material properties of in situ Portland cement-stabilized pavement layers. The material inputs of strength and stiffness can be captured using the Clegg hammer, DCP, SSG, PFWD, and PSPA. This project sought to validate that the measurements collected in situ using the portable test devices can be accurately correlated to strength and stiffness as determined by UCS, flexural strength, repeated-load, and FWD testing. The ability to input correlated measurements collected using these devices into existing pavement evaluation programs to predict the occurrence of failure indicating pavement distresses was investigated. Prospective users of this report include all DoD users responsible for the evaluation of unsurfaced stabilized soil airfields.

Laboratory testing

Heymsfield et al. (2007) determined that the material properties of strength and stiffness are required to accurately model the mechanical performance of cement-stabilized soil layers. The strength of a material is defined as the capacity for resistance of an applied load (Transportation Research Board (TRB) 1999). The two primary modes of strength exhibited by pavement layers are compressive and flexural strength. The ability of a material to resist deflection due to an imparted force defines the stiffness (TRB 1999). When considering pavement layers, the stiffness of the

material determines the magnitudes of displacement and strain experienced as a result of being loaded. The strength and stiffness of the material are essential to modeling the performance of the pavement layer, but the performance of the material is strongly influenced by other properties of the material, such as cement content, number of internal flaws, tensile stress and strain, Poisson's ratio, and current stress level (Hadley 1991).

The laboratory testing of samples recovered from the field evaluations consisted of UCS testing in accordance with American Society for Testing and Materials (ASTM 2006) test method D 1633, flexural strength testing in accordance with ASTM D 1635, stiffness determination by repeated compressive loading in accordance with ASTM D 3999, and cement content determination in accordance with ASTM D 806.

In addition to the laboratory testing, stiffness values for the stabilized surface and subgrade were backcalculated using deflection data measured in the field using the FWD. The backcalculation was accomplished using the evaluation module of the Pavement-Transportation Computer Assisted Structural Engineering (PCASE) software package.

Unconfined compressive strength

The compressive strength of a material defines its ability to resist axial loading. The compressive strength of stabilized materials is often quantified by measuring the UCS. The UCS provides an indicator of the maximum load carrying capacity that can be expected from the material under unconfined conditions.

The standard method for determining the UCS of stabilized materials is in accordance with ASTM D 1633, "Standard test methods for compressive strength of molded soil-cement cylinders." The UCS is determined in the standard method by loading a cylindrical specimen of stabilized soil with an increasing axial load until the material reaches failure. A stabilized soil sample undergoing UCS testing is shown in Figure 6.

Failure is defined as the point at which the specimen will no longer resist increases in load (Lade 2002). The maximum load, which is achieved before failure of the specimen, is the ultimate load, the value of which is divided by the cross-sectional area of the specimen to yield the UCS of the material (Equation 1).

Figure 6. UCS testing on sample.

$$UCS = \frac{P_{Ultimate}}{A} \tag{1}$$

where:

$P_{Ultimate}$ = maximum load applied to sample
A = cross-sectional area of sample.

Modulus of rupture

The ability of a solid to resist fracture in bending is the flexural strength of the material and is also known as the modulus of rupture (R). The flexural strength of a stabilized soil material can be determined using a simple beam with third-point loading as provided in ASTM D 1635, “Standard test method for flexural strength of soil-cement using simple beam with third-point loading.” In accordance with ASTM D 1635, a prismatic beam of stabilized material is placed on its side with respect to the molded position in the loading frame. The beam is then loaded vertically at the third point until the specimen reaches failure. Third-point loading of a stabilized soil beam is shown in Figure 7. The ultimate load reached before failure of the

specimen is used along with the geometry of the beam and the loading configuration to determine the flexural strength (Equation 2).

$$R = \frac{PL}{bd^2} \tag{2}$$

where:

P = maximum applied load
L = span length
b = average width of specimen
d = average depth of specimen.

Figure 7. Flexural strength testing using third-point loading.

Elastic modulus

Stiffness is used interchangeably with the terms elastic modulus, Young's modulus, and resilient modulus (M_R) when referring to pavement layers. The elastic modulus of stabilized materials can be determined in the laboratory using the standard test method ASTM D 3999, "Standard test methods for the determination of the modulus and damping properties of

soils using the cyclic triaxial apparatus." In this method, the elastic modulus is determined by taking the ratio of the peak stress and strain of the loaded specimen to the relaxed stress and strain of the unloaded specimen in a representative load cycle to determine the elastic modulus (Equation 3).

$$E = \frac{(\sigma_{Peak} - \sigma_{Relaxed})}{(\varepsilon_{Peak} - \varepsilon_{Relaxed})} \tag{3}$$

where:

σ_{Peak} = peak stress of load cycle
$\sigma_{Relaxed}$ = stress at relaxed state
ε_{Peak} = peak strain of load cycle
$\varepsilon_{Relaxed}$ = strain at relaxed state.

A loading cycle includes unloaded specimen, gradual application of a predetermined controlled load, controlled unloading, and return to an unloaded state. The loading cycle is repeatedly applied to the specimen to simulate actual traffic loading. A typical triaxial testing setup is shown in Figure 8.

The elastic modulus of stabilized soils can also be estimated in the field using standard test method ASTM D 4694, "Standard test method for deflections with a falling-weight-type impulse load device." An impact load is measured at the center of a circular loading plate, and the resulting deflection in the surface is measured at the plate center and also radially outward. The imparted load divided by the surface deflection measured at the center of the loading plate defines the stiffness of the material. The elastic modulus is estimated using the deflection basin measurements and an iterative backcalculation process. Modulus values are assigned to each of the defined pavement layers, and the resulting deflections are predicted as a result of the impulse load. The modulus values are varied within defined limits, considered typical for the material tested, until the closest representation of the original deflection measurements can be simulated. Measuring the elastic modulus with a trailer-mounted FWD is depicted in Figure 9.

Figure 8. Cyclic triaxial testing on stabilized soil sample.

Figure 9. Failing-weight deflectometer testing of stabilized surface.

Portland cement content

The strength and stiffness exhibited by stabilized soils are determined by a number of factors. The cement content of a Portland cement-stabilized blend is extremely influential on the development of strength and stiffness in addition to several other properties. Stabilization additives directly affect the material properties and limiting states of the parent soils, influencing the ability to model the performance of the stabilized soil blend (Tingle et al. 2004). Therefore, the cement content of the stabilized mixture must be quantified to effectively characterize the material.

The cement content was determined by a chemical analysis according to ASTM D 806, "Standard test method for cement content of hardened soil-cement mixtures." The basis of the method is that the calcium oxide (CaO) content of Portland cement is very high compared with the content of natural soils. The CaO content of the stabilized soil mixture is therefore a good indicator of cement content. The chemical analysis employs titration and filtration processes to determine the CaO content of the natural parent soil, the Portland cement used in construction, and the stabilized soil blend. The percentages of CaO in each of the components and in the blend are then compared to determine the percent by weight of Portland cement in the stabilized mix, as shown in Equation 4.

$$Cement\ Content = \frac{(G-F)}{(E-F)} \times 100 \tag{4}$$

where:

G = percent CaO in stabilized soil mixture
F = percent CaO in parent soil
E = percent CaO in Portland cement

Pavement evaluation software

The PCASE is a pavement design and evaluation computer software application currently employed by the DoD. The evaluation protocol used in the program is based upon the standards set forth in Unified Facilities Criteria (UFC) 3-260-02 and 3-260-03 (Joint Departments 2001a,b) for airfield pavement design and evaluation, respectively.

The PCASE evaluation program uses a linear elastic model to conduct the mechanistic analysis of pavement layers. Up to five layers may be used during the evaluation. Bush and Samuel (1986) determined in a study of ALRS that layered elastic models could be used to predict the performance of stabilized soil layers. Burmister's solutions are used in the analysis to determine the stresses and strains in the critical locations of the pavement system. The magnitudes of the responses are used to determine the occurrence and severity of distresses developed in the pavement using an empirical approach. Using established failure criteria, the maximum allowable aircraft coverages and loading are determined. The evaluation module of the PCASE pavement evaluation and design software is shown in Figure 10.

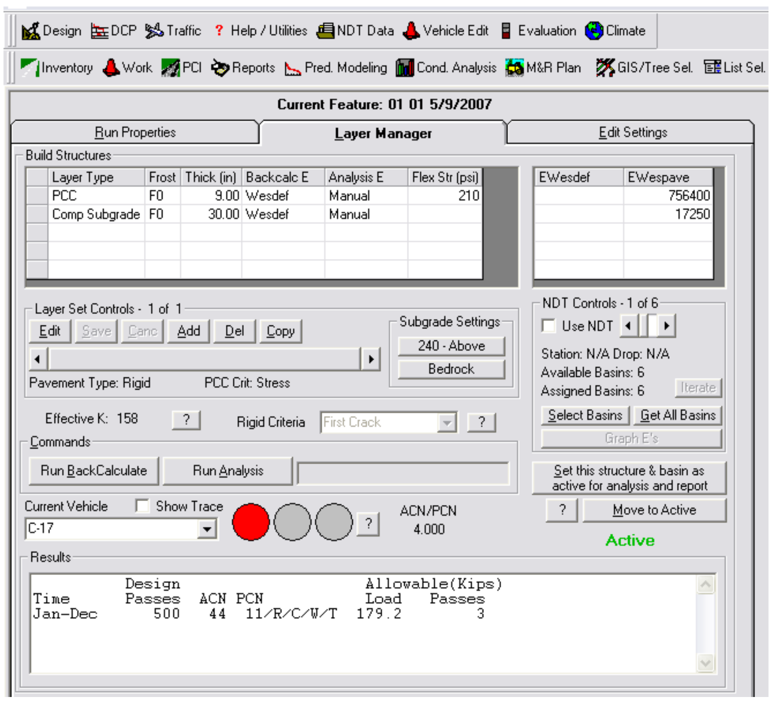

Figure 10. PCASE evaluation module.

3 In Situ Evaluation of Stabilized Surfaces

Site assessment

In situ test devices were used to examine existing stabilized soil-surfaced airfields, to evaluate the feasibility of using the devices to conduct in situ material characterization needed to determine allowable aircraft loads and remaining service life. The test sites included three unsurfaced stabilized-soil airfields (All-American Landing Zone (AALZ) at Camp Robinson, AR; Fullerton Landing Zone (FLZ), at Fort Polk, LA; and Self Landing Zone (SLZ), also at Fort Polk, LA) and a stabilized soil pavement base course test section (BCTS) at the ERDC, Vicksburg, MS. An additional test section was constructed at the ERDC to serve as a model verification test section (VTS). Further details on the VTS are presented in Chapter 5. The test sites evaluated were all stabilized with Portland cement.

Ten representative test locations on each of the airfields, four representative locations on the BCTS, and five representative locations on the VTS were identified and marked to ensure data collection on the same material sample. Each test location was tested using the Clegg hammer, DCP, SSG, PFWD, and PSPA. After testing with the in situ devices, FWD tests were conducted at each of the locations in accordance with ASTM D 4694. The stabilized surface was then penetrated using an impact drill to create a 1-in. access hole to the subgrade. The DCP was used to determine the level of subgrade support.

In situ test devices

Clegg hammer

Testing with the Clegg hammer was conducted in accordance with manufacturer specifications and standard test method ASTM D 5874, "Standard test method for determination of the impact value (IV) of a soil." Care was taken to ensure that each test location was level and free of debris. The device was then placed on the marked test location and the safety pin removed. The mass was then raised until the inscribed white line on the hammer was level with the top edge of the guide tube. The mass was then released and allowed to impact the surface and the CIV measurement collected. The above procedure was repeated four times at each test location and the peak value recorded.

Dynamic cone penetrometer

Testing with the DCP was conducted in accordance with ASTM D 6951, “Standard test method for use of the dynamic cone penetrometer in shallow pavement applications.” Once assembled, the DCP was operated by placing the conical tip on the surface at the marked test location. The hammer was then raised to the top of the drop rod, released, and allowed to impact the anvil. This process was repeated until the conical tip passed through the pavement layer of interest. A measurement of the penetration of the device was taken at intervals of roughly 0.787 in. (20 mm) based upon fixed points on the surface and on the device. The blow count, or number of hammer impacts required to penetrate the measured distance, was also recorded. At the conclusion of testing, the blow count is used to determine the DCP index, or millimeters of penetration per blow. The DCP index was used to estimate the bearing capacity of the material tested. Common correlations between DCP index and California bearing ratio (CBR) are presented in Equations 5–7.

$$CBR = \frac{292}{(DCP\ Index)^{1.12}} \tag{5}$$

$$CL\ Soils\ CBR < 10 : CBR = \frac{1}{(0.017019 \times DCP\ Index)^{2}} \tag{6}$$

$$CH\ Soils : CBR = \frac{1}{(0.002871 \times DCPIndex)} \tag{7}$$

Soil stiffness gauge

Testing with the SSG was conducted in accordance with manufacturer specifications and standard test method ASTM D 6758, “Standard test method for measuring stiffness and apparent modulus of soil and soil-aggregate in-place by an electro-mechanical method.” The SSG was operated by first inspecting the steel ring and ensuring that it was clean and free of debris. The device was then placed on the surface of the marked test location. The apparatus was then pushed into the surface with mild force (≈ 10 lb) and rotated a quarter turn. Care was taken to ensure that 60% of the ring surface was in contact with the tested material. Three measurements were taken, and the average stiffness and elastic modulus were

recorded. A Poisson's ratio for cement-stabilized materials of 0.20 was used to calculate the elastic modulus.

Portable falling-weight deflectometer

The PFWD was operated in accordance with manufacturer specifications. The load plate of the PFWD was placed on the stabilized surface at the marked test location. Each test was performed by raising the mass to the safety release, then releasing the mass and allowing it to impact an assembly of rubber buffers. The impact load and deflection at the center of the load plate was recorded in addition to the deflection at two additional geophones using the controlling laptop. Three test repetitions were performed, and the average impact load, deflection, and modulus values were recorded.

Portable seismic property analyzer

Testing with the PSPA was conducted in accordance with manufacturer recommendations and ERDC/GSL SR-06-9 (Bell 2006a). Tests were accomplished by placing the device on the surface at the marked test location and ensuring the source and receivers were in contact with the material surface. The material properties were defined through user inputs on the laptop to include approximate values for density (130 lbf/ft^3, ~2082 kg/m^3) and Poisson's ratio (0.20). Once the initial setup was complete, the device was activated using the laptop. Three tests were performed at each test location, and an average elastic modulus value was recorded.

Material sampling

At the conclusion of in situ surface and subgrade material characterization, samples were recovered from three of the ten representative locations on each existing airfield surface and returned to the materials laboratory at the ERDC for testing. From each existing airfield, four 4-in. (102-mm) core samples were taken from each of the three representative testing locations in addition to an 18-in. × 18-in. (457-mm × 457-mm) slab through the depth of the stabilized soil material. In total, 36 core samples (Figure 11) and three slabs (Figure 12) were removed from the sampled test sites for laboratory testing at the ERDC. Twenty-seven cores were tested for UCS, nine cores were tested in repeated-load compression, and three

Figure 11. Core sample recovered from existing airfield.

Figure 12. Recovered stabilized surface slab sample.

3-in. × 3-in. × 11.25-in. (76.2-mm × 76.2-mm × 286-mm) beams were cut from each of the recovered slabs to test in third-point loading. The stabilizer content testing was conducted using samples previously failed in UCS. Samples were not recovered from the BCTS due to potential of influencing the properties of the layer prior to supplementary testing.

4 Testing Results

Presentation of collected data

The in situ measurements collected with the Clegg hammer, DCP, SSG, PFWD, and PSPA are presented in Table 1. The data from the laboratory testing of samples removed from the Portland cement-stabilized layers are presented in Table 2.

Table 1. In situ test device measurements.

Test Site	Surface Thickness in.	Clegg Hammer (CIV)	DCP Index	SSG Elastic Modulus psi	PFWD Elastic Modulus psi	PSPA Elastic Modulus psi
AALZ 1	10	84	1	23,082	1,133,900	1,350,000
AALZ 2	9	88	0	21,768	1,594,517	1,953,333
AALZ 3	10	85	0	48,474	1,505,100	2,060,000
AALZ 4	9	82	0	25,486	1,673,783	2,336,667
AALZ 5	11	84	0	24,069	1,847,783	1,773,333
AALZ 6	11	87	0	21,902	2,198,683	1,573,333
AALZ 7	11	83	0	26,054	1,325,300	1,636,667
AALZ 8	11	86	0	34,091	1,616,750	1,310,000
AALZ 9	11	84	0	44,949	1,276,483	2,016,667
AALZ 10	10	85	0	25,820	1,724,050	2,350,000
AVERAGE	**10**	**85**	**0**	**29,569**	**1,589,635**	**1,836,000**
FLZ 1	12	80	1	22,556	241,667	486,667
FLZ 2	13	60	3	21,745	154,183	1,360,000
FLZ 3	13	86	0	27,761	614,800	396,667
FLZ 4	11	84	2	23,111	924,617	607,500
FLZ 5	11	82	__[a]	57,809	630,750	836,667
FLZ 6	10	85	__[a]	32,727	260,517	903,333
FLZ 7	11	85	__[a]	35,837	895,133	3,013,333
FLZ 8	11	75	__[a]	31,840	133,883	1,596,667
FLZ 9	16	39	3	20,497	249,883	1,913,333
FLZ 10	11	83	1	41,382	584,833	852,500
AVERAGE	**12**	**76**	**1**	**31,526**	**469,027**	**1,196,667**
SLZ 1	6	82	__[a]	26,757	1,247,483	526,667
SLZ 2	8	84	__[a]	27,527	2,717,300	1,216,667
SLZ 3	8	76	__[a]	25,226	1,453,625	913,333
SLZ 4	9	84	__[a]	26,382	1,533,617	630,000
SLZ 5	9	86	__[a]	24,595	1,667,017	1,043,333

SLZ 6	7	84	—[a]	23,355	1,580,017	1,070,000
SLZ 7	9	85	—[a]	21,504	1,251,350	1,596,667
SLZ 8	7	44	—[a]	13,341	324,800	1,696,667
SLZ 9	10	84	—[a]	31,786	3,103,483	1,866,667
SLZ 10	8	47	—[a]	20,903	783,000	1,036,667
AVERAGE	**8**	**75**	**—[a]**	**24,138**	**1,566,169**	**1,159,667**
BCTS 1	4	26	—[a]	43,117	150,667	128,333
BCTS 2	4	50	—[a]	37,991	270,667	410,000
BCTS 3	4	30	—[a]	46,345	149,000	158,333
BCTS 4	4	55	—[a]	46,593	293,667	380,000
AVERAGE	**4**	**40**	**—[a]**	**43,511**	**216,000**	**269,167**

[a] Surface evaluation using the DCP discontinued after 15 initial tests.

Table 2. Standard test method measurements.

Test Site	UCS psi	Flex Strength psi	Repeated-load Modulus psi	FWD Modulus psi	Cement Content %
AALZ 1	—[a]	—[a]	—[a]	216,602	—[a]
AALZ 2	1,395	—[a]	—[a]	406,247	7
AALZ 3	—[a]	—[a]	—[a]	231,409	—[a]
AALZ 4	1,212	183	540,182	383,744	10
AALZ 5	—[a]	—[a]	—[a]	366,107	—[a]
AALZ 6	—[a]	—[a]	—[a]	258,216	—[a]
AALZ 7	—[a]	—[a]	—[a]	194,918	—[a]
AALZ 8	1,107	—[a]	—[a]	162,462	9
AALZ 9	—[a]	—[a]	—[a]	129,991	—[a]
AALZ 10	—[a]	—[a]	—[a]	219,257	—[a]
AVERAGE	**1,238**	**183**	**540,182**	**256,895**	**9**
FLZ 1	575	—[a]	—[a]	152,934	16
FLZ 2	—[a]	—[a]	—[a]	203,195	—[a]
FLZ 3	—[a]	—[a]	—[a]	1,249,510	—[a]
FLZ 4	—[a]	—[a]	—[a]	1,171,695	—[a]
FLZ 5	1,195	131	306,070	406,474	12
FLZ 6	—[a]	—[a]	—[a]	209,426	—[a]
FLZ 7	—[a]	—[a]	—[a]	515,033	—[a]
FLZ 8	—[a]	—[a]	—[a]	202,954	—[a]
FLZ 9	—[a]	—[a]	—[a]	298,783	—[a]
FLZ 10	987	—[a]	—[a]	520,080	9
AVERAGE	**919**	**131**	**306,070**	**493,008**	**12**
SLZ 1	—[a]	—[a]	—[a]	282,553	—[a]
SLZ 2	889	—[a]	—[a]	506,870	11

SLZ 3	—[a]	—[a]	—[a]	117,321	—[a]
SLZ 4	876	—[a]	—[a]	169,128	7
SLZ 5	—[a]	—[a]	—[a]	335,921	—[a]
SLZ 6	—[a]	—[a]	—[a]	284,130	—[a]
SLZ 7	—[a]	—[a]	—[a]	345,030	—[a]
SLZ 8	—[a]	—[a]	—[a]	98,740	—[a]
SLZ 9	607	44	271,513	562,581	7
SLZ 10	—[a]	—[a]	—[a]	161,957	—[a]
AVERAGE	790	44	271,513	286,423	8
BCTS 1	—[a]	—[a]	—[a]	22,571	—[a]
BCTS 2	—[a]	—[a]	—[a]	23,549	—[a]
BCTS 3	—[a]	—[a]	—[a]	35,993	—[a]
BCTS 4	—[a]	—[a]	—[a]	34,602	—[a]
AVERAGE	—[a]	—[a]	—[a]	29,179	—[a]

[a] Sample data not collected.

Evaluation of the stabilized soil surface with the DCP was discontinued after 15 test locations. The stabilized surface was discovered to be sufficiently stiff as to retard penetration of the material with the conical tip. This resulted in a “refusal” of the DCP test and, therefore, additional testing was not attempted. It should be noted that all of the surfaces investigated provided bearing capacities in excess of 100 CBR at the time of testing.

Regression analysis

An objective of this research was to identify relationships between measurements collected in the field using the in situ test devices and the material properties determined using standard test methods. A regression analysis is the development of a probabilistic relationship describing one random variable as a function of another variable (Ang and Tang 2007). As applied to this project, relationships were developed between the field measurements of strength and stiffness collected with the in situ test devices and the measurements collected using the standard test methods. The precision of the proposed relationship will be determined using the coefficient of determination or R^2 value. The range of R^2 values is from 1 to 0, with higher values indicating lower conditional variance and inspiring greater confidence in being able to predict the value of one variable based on another (Ang and Tang 2007).

Regression analyses were conducted between measurements collected with each of the in situ test devices and the standard test methods for strength and stiffness. The analyses were conducted by plotting a scattergram using the in situ measurements as the independent variable and the standard test method measurements as the dependent variable. Linear and nonlinear correlations were attempted, and the effectiveness of the relationships was determined by the R^2 value. The correlation with the highest R^2 value was established as the most effective relationship for predicting a given standard test method using a particular in situ test device. The scattergrams for the developed regressions are presented in Figures 13 through 28.

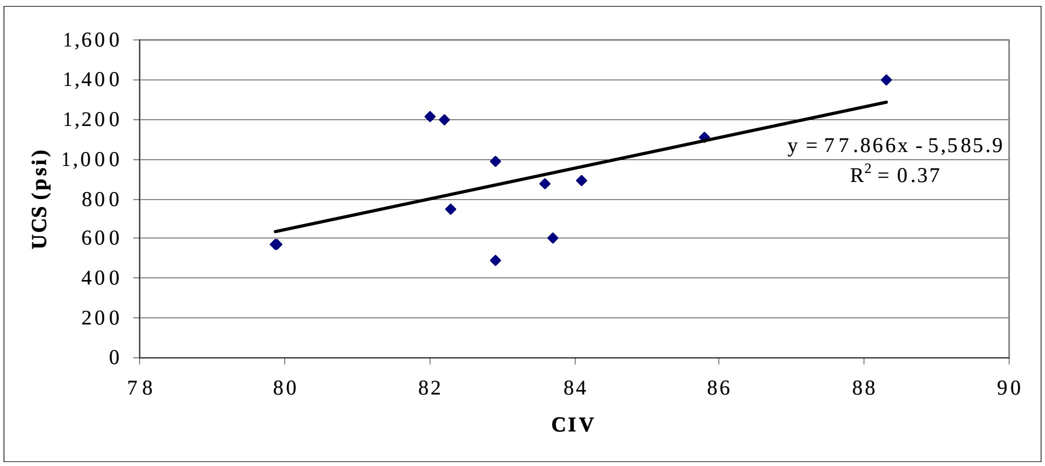

Figure 13. Clegg hammer UCS correlation.

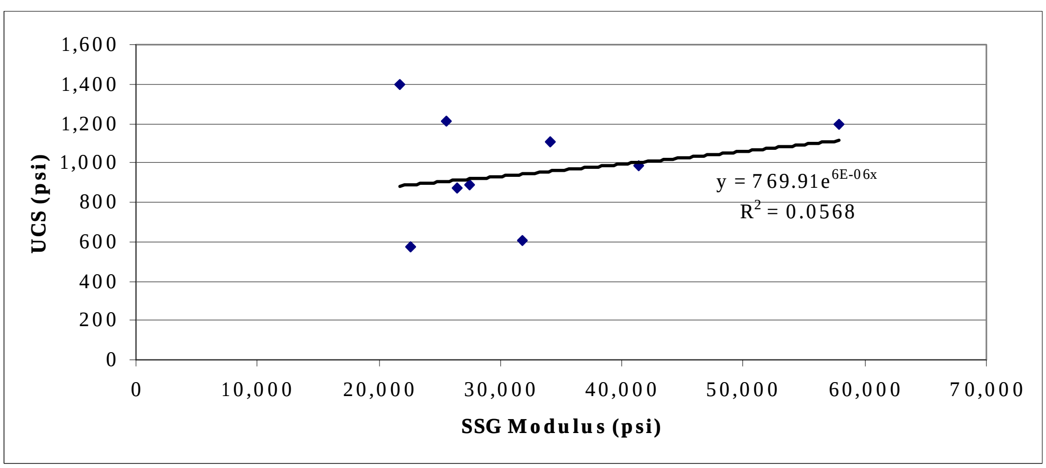

Figure 14. SSG UCS correlation.

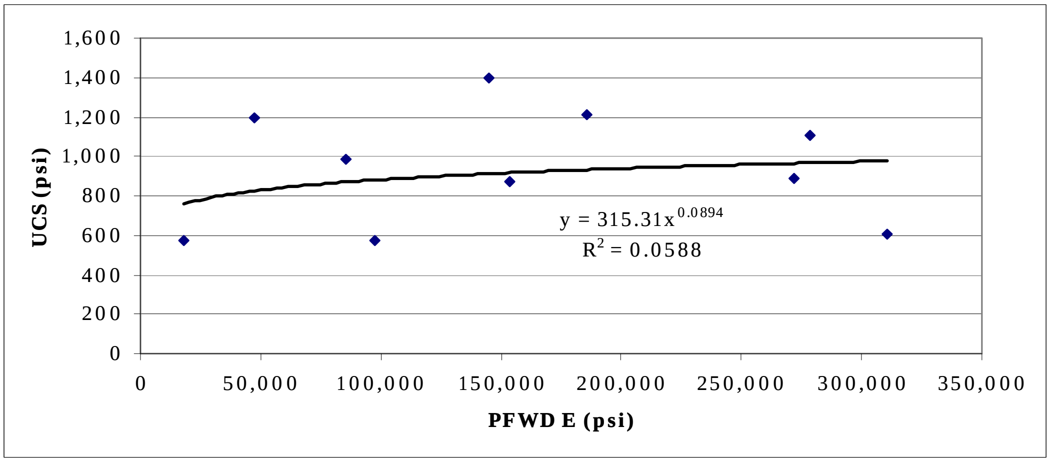

Figure 15. PFWD UCS correlation.

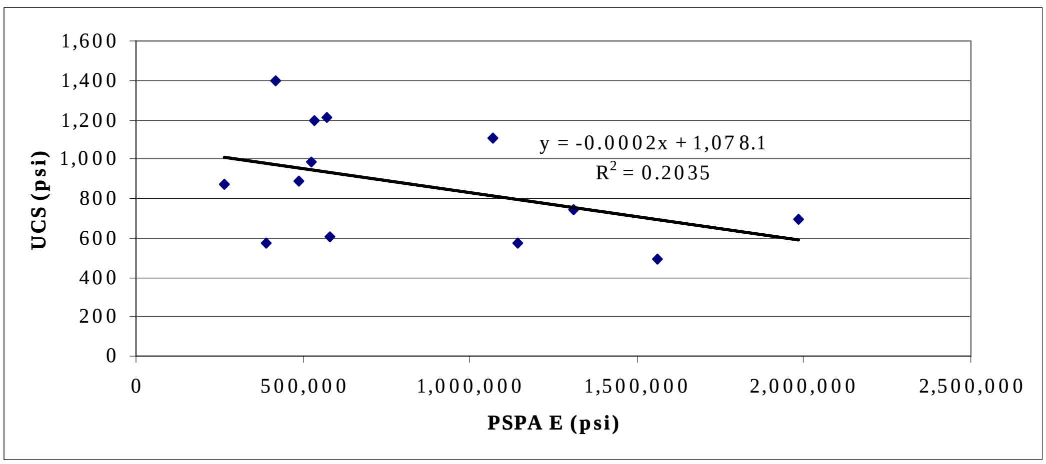

Figure 16. PSPA UCS correlation.

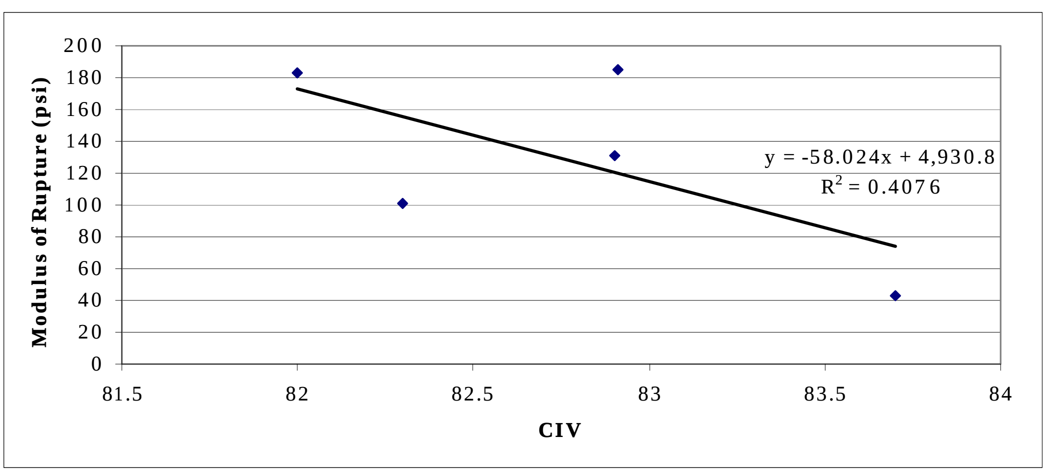

Figure 17. Clegg hammer modulus of rupture correlation.

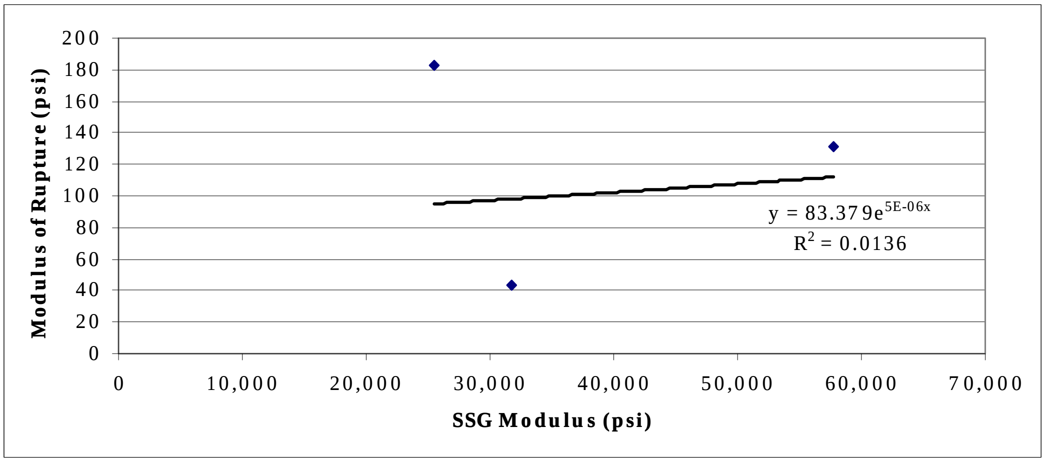

Figure 18. SSG modulus of rupture correlation.

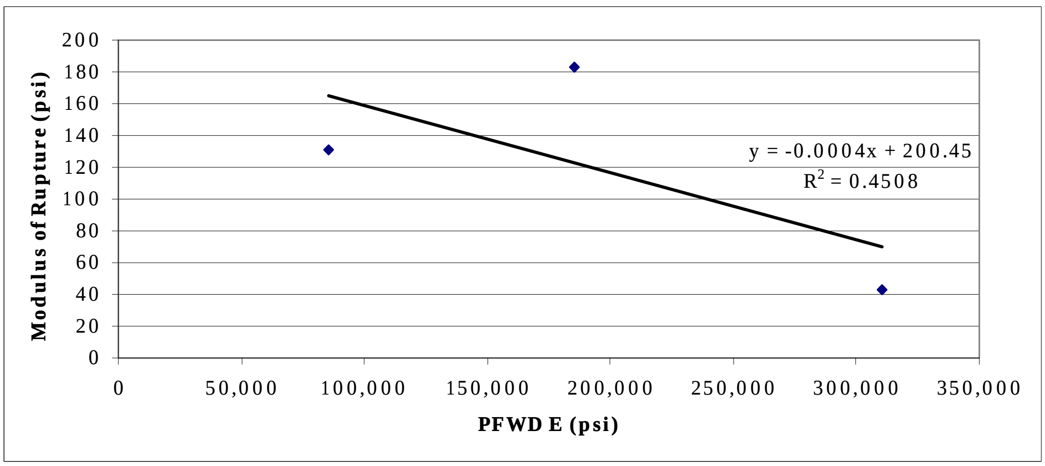

Figure 19. PFWD modulus of rupture correlation.

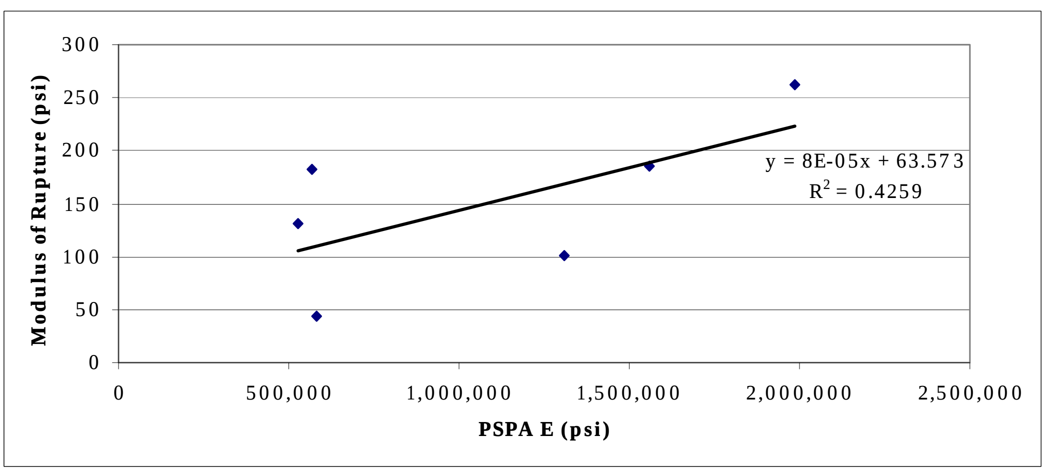

Figure 20. PSPA modulus of rupture correlation.

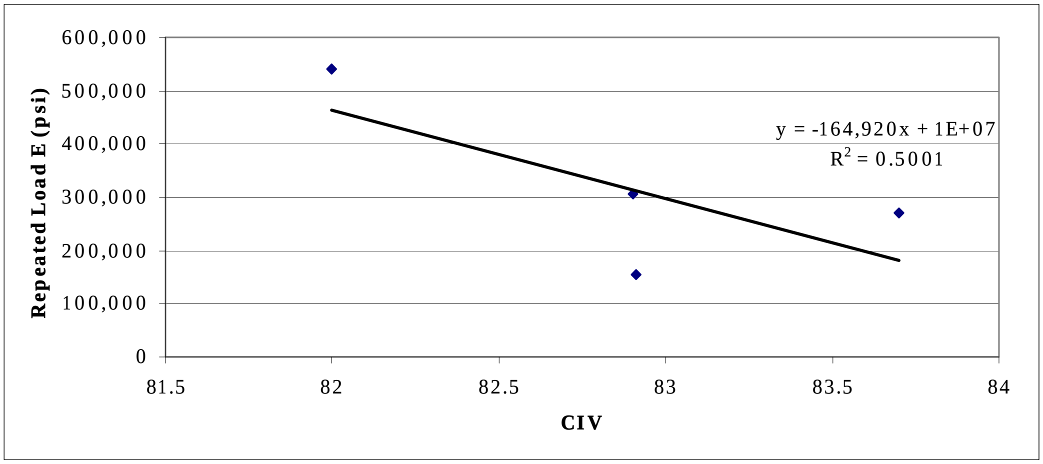

Figure 21. Clegg hammer repeated-load modulus correlation.

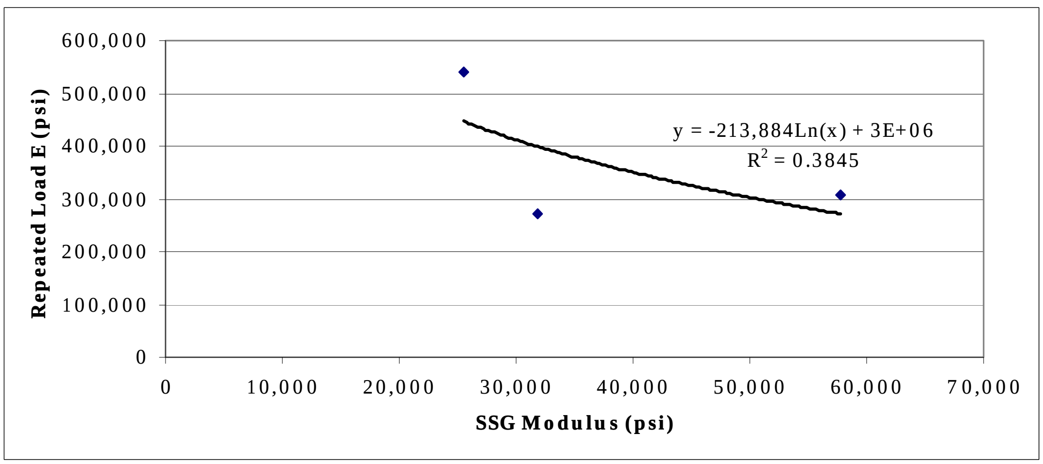

Figure 22. SSG repeated-load modulus correlation.

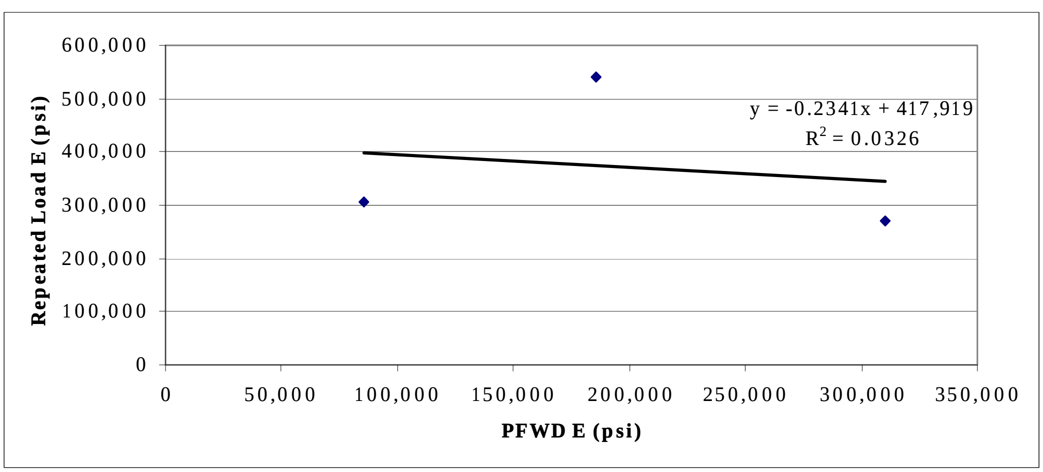

Figure 23. PFWD repeated-load modulus correlation.

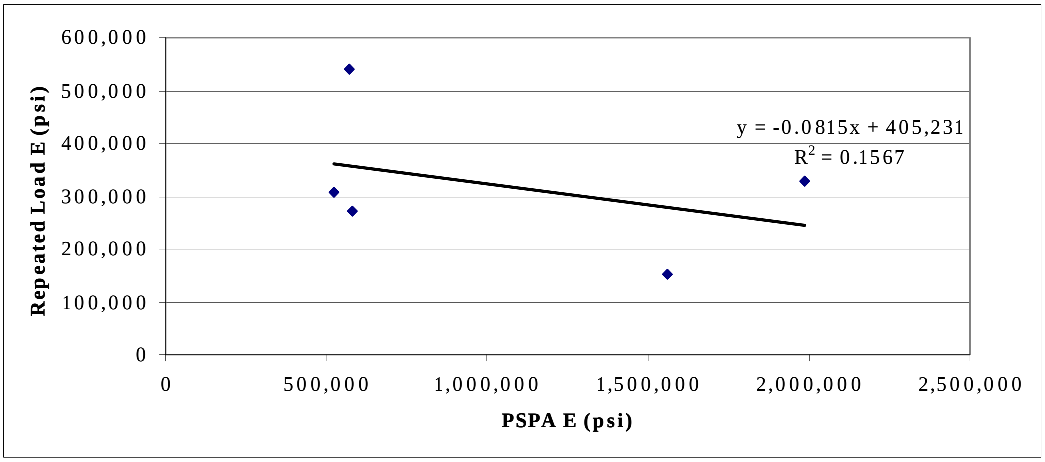

Figure 24. PSPA repeated-load modulus correlation.

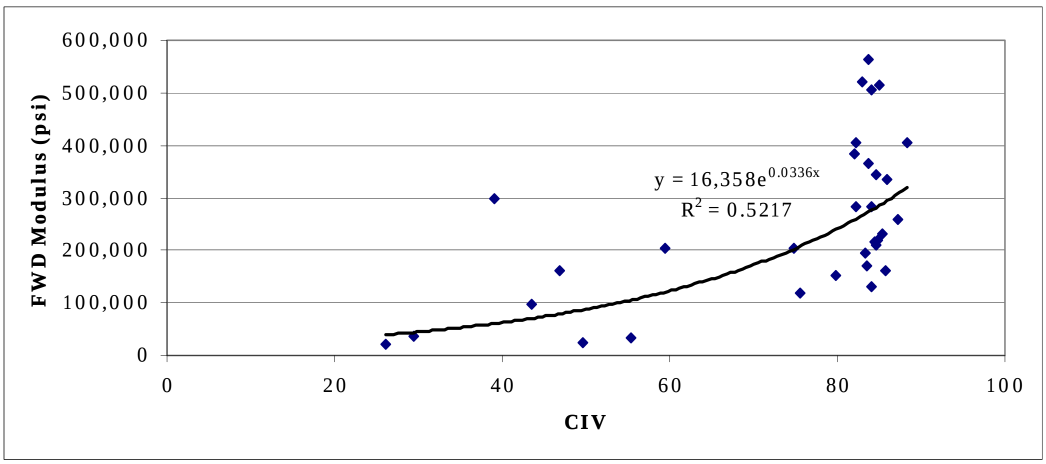

Figure 25. Clegg hammer FWD modulus correlation.

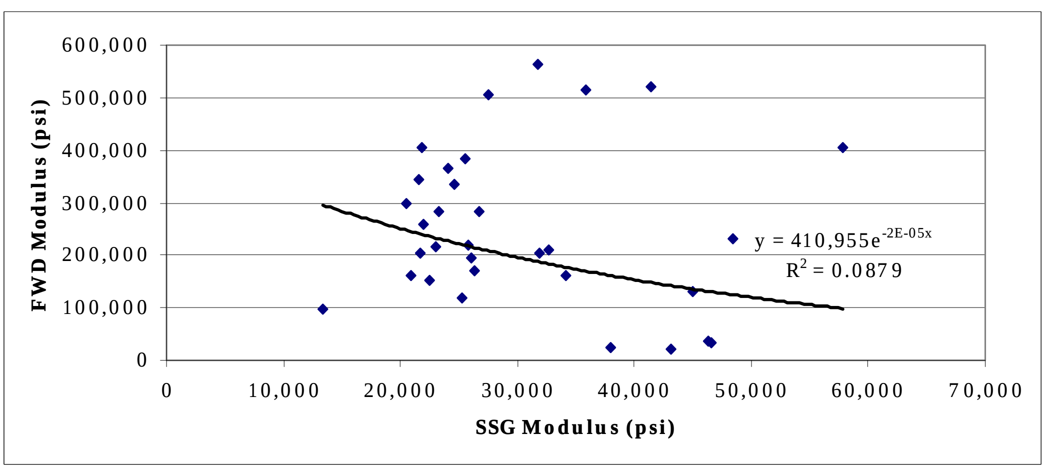

Figure 26. SSG FWD modulus correlation.

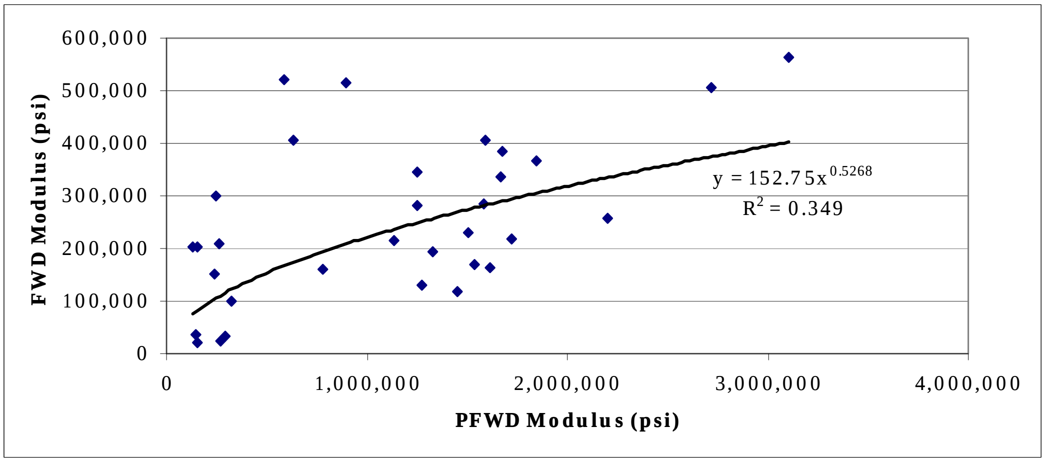

Figure 27. PFWD FWD modulus correlation.

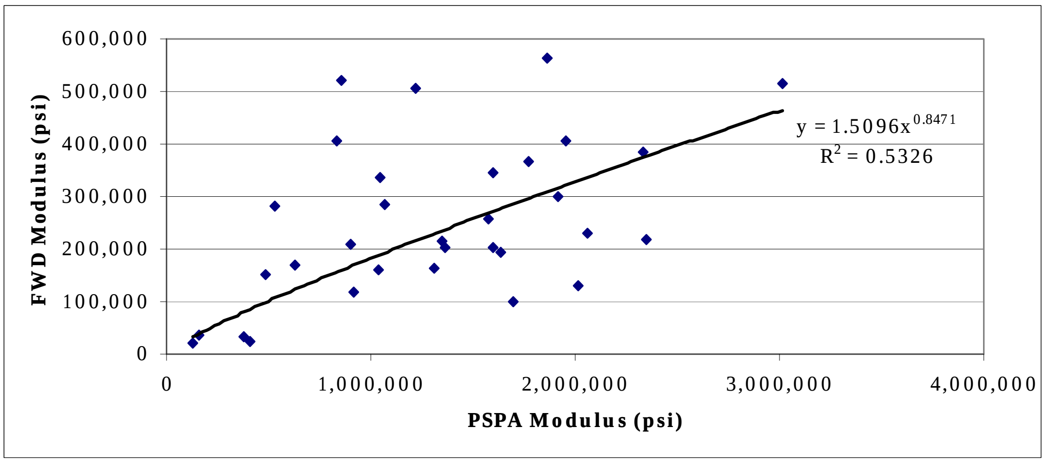

Figure 28. PSPA FWD modulus correlation.

The strength of each relationship was determined by conducting a regression analysis and reviewing the R^2 value. Table 3 summarizes the relationships and the associated R^2 developed in this study as well as those previously documented by others. The most effective in situ devices for the prediction of UCS and flexural strength, based on the R^2 value, were the Clegg hammer and PFWD, respectively. The most effective in situ devices for predicting elastic modulus as determined by cyclic compression loading and backcalculated FWD measurements were the PSPA and Clegg hammer, respectively.

The accuracy of the predictions made using the correlations was quantified by calculating the root mean squared error (RMSE). The RMSE provides a measure of the accuracy of a predictive model by measuring the difference between the predicted and observed values (Equation 8). Each correlation

Table 3. Material property correlations.

Correlation	Material Property	Equation	Correlated Data Range	R^2	RMSE
Clegg - UCS	UCS (psi)	UCS = 77.866(CIV) - 5,585.9	79 < CIV < 88	0.37	226
SSG - UCS	UCS (psi)	$UCS = 769.91e^{6E-06(E)}$	$21,700 < E_{SSG} < 57,800$	0.06	259
PFWD - UCS	UCS (psi)	$UCS = 315.31(E_{PFWD})^{0.0894}$	$241,600 < E_{PFWD} < 3,103,400$	0.06	275
PSPA - UCS [b]	UCS (psi)	$UCS = -0.0002(E_{PSPA}) + 1,078.1$	$486,600 < E_{PSPA} < 2,336,600$	0.20	252
Okamoto et al.	UCS (psi)	log(UCS) = 0.081 + 1.309[log(CIV)]	5 < CIV < 175	0.90 [a]	567
Freeman et al.	UCS (psi)	UCS = 12.51(CIV) - 285.9	30 < CIV < 70	0.99 [a]	300
Clegg - R [b]	Modulus of rupture (psi)	R = -58.024(CIV) + 4,930.8	82 < CIV < 84	0.41	41
SSG - R	Modulus of rupture (psi)	$R = 83.379e^{5E-06(E)}$	$25,400 < E_{SSG} < 57,800$	0.01	62
PFWD - R [b]	Modulus of rupture (psi)	$R = -0.0004(E_{PFWD}) + 200.45$	$85,200 < E_{PFWD} < 310,300$	0.45	43
PSPA - R	Modulus of rupture (psi)	$R = 8.034E-05(E_{PSPA}) + 63.573$	$525,000 < E_{PSPA} < 1,984,400$	0.43	53
Bell	Modulus of rupture (psi)	$R = 0.12(E_{PSPA})$	$3,000,000 < E_{PSPA} < 6,500,000$	0.53 [a]	61
Clegg - FWD	FWD elastic modulus (psi)	$E = 16,358e^{0.0336(CIV)}$	26 < CIV < 88	0.52	255,100
SSG - FWD [b]	FWD elastic modulus (psi)	$E = 410,955e^{-2E-05(E)}$	$13,300 < E_{SSG} < 57,800$	0.09	276,851
PFWD - FWD	FWD elastic modulus (psi)	$E = 152.75(E_{PFWD})^{0.5268}$	$133,800 < E_{PFWD} < 3,103,400$	0.35	277,772
PSPA - FWD	FWD elastic modulus (psi)	$E = 1.5096(E_{PSPA})^{0.8471}$	$128,300 < E_{PSPA} < 3,013,300$	0.53	298,695
Nazzal (SSG)	FWD elastic modulus (MPa)	$E = -20.07 + 1.17(E_{SSG})$	$40.8 < E_{SSG} < 194.4$	0.81 [a]	385,673
Nazzal (PFWD)	FWD elastic modulus (MPa)	$E = 0.97(E_{PFWD})$	$12.5 < E_{PFWD} < 865$	0.94 [a]	1,045,310
Clegg – Cyclic E [b]	Cyclic elastic modulus (psi)	E = -164,920(CIV) + 13,985,972	82 < CIV < 84	0.50	99,203
SSG - Cyclic E [b]	Cyclic elastic modulus (psi)	$E = -213,884[Ln(E_{SSG})] + 3E+06$	$25,400 < E_{SSG} < 57,800$	0.38	417,084
PFWD – Cyclic E [b]	Cyclic elastic modulus (psi)	$E = -0.2341(E_{PFWD}) + 417,919$	$85,200 < E_{PFWD} < 310,300$	0.03	117,381
PSPA - Cyclic E [b]	Cyclic elastic modulus (psi)	$E = -0.0815(E_{PSPA}) + 405,231$	$525,000 < E_{PSPA} < 1,984,400$	0.16	115,331
Hilbrich	Cyclic elastic modulus (psi)	$E = 0.7415*(E_{PSPA})$	$450,000 < E_{PSPA} < 3,000,000$	0.93 [a]	686,506

[a] Coefficient of determination calculated in original study.

[b] Relationship trend does not indicate appropriate relationship.

was used to predict the strength properties of the tested materials using the in situ test device data. The predicted property value was then compared with the standard test method value and the RMSE calculated.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left[f\left(x_i\right)-y_i\right]^2}{n}} \tag{8}$$

where:

$f(x_i)$ = value predicted using correlation
y = observed value
n = number of data points.

To determine the accuracy of the developed relationships in addition to those obtained from the literature review, the RMSE was determined. The RMSE for each relationship is presented in Table 3. The most accurate predictors of UCS, modulus of rupture, FWD elastic modulus, and repeated-load elastic modulus, as indicated by lower RMSE values, were the correlations developed in this study using the in situ measurements collected with the Clegg hammer.

Determination of Portland cement content

The inclusion of Portland cement affects the gradation, plasticity, and mechanical properties of the cement-stabilized soil. The cement content of the stabilized mixture is also the most direct indicator of the strength gain to be expected in the final material blend. Strength gain in stabilized materials is a result of the increased stability of interparticle contacts caused by increased internal friction and cohesion (Tingle et al. 2004). Cement content testing was conducted on all of the sampled materials in accordance with ASTM D 806. Because of the relatively low Portland cement content of cement-stabilized soil and the inconsistency of in-place mixing techniques, variability occurs between the design and constructed Portland cement content for the evaluated stabilized layers, as shown in Table 4.

Table 4. Target versus actual cement content.

Site Name (Abbreviation)	Location	USCS Classification	Description	Target Portland cement content [a]	Actual Portland cement content [b]
All-American Landing Zone (AALZ)	Camp Robinson, AR	SW-SM	Gray silty-sand	9	8.7
Fullerton Landing Zone (FLZ)	Fort Polk, LA	SP	Reddish-brown sand	9	12.6
Self Landing Zone (SLZ)	Fort Polk, LA	SW	Light gray sand	9	9.2
ERDC Base Course Test Section (BCTS)	Vicksburg, MS	GC	Reddish-brown gravel w/fines	—[c]	—[c]
ERDC Verification Test Section (VTS)	Vicksburg, MS	SM	Yellow-brown silty-sand	8	14.3

[a] Percent by weight as determined in mix design.
[b] Percent by weight as determined using ASTM D806 standard test method.
[c] Mix design and content testing not conducted.

The mixed-in-place soil stabilization technique creates a heterogeneous soil-cement blend with great variability in Portland cement content and moisture distribution. Hadley (1991) measured significant levels of variation with respect to the material properties of cement content, elastic modulus, Poisson's ratio, ultimate tensile stress and strain, and cycles-to-failure within a single material blend test item. The great amount of variability in determining material properties extends to the models incorporating the material property data.

Performance prediction

The PCASE software application was used to evaluate and predict the performance of the unsurfaced stabilized soil airfields. The mechanical performance of stabilized soil layers is complex, nonuniform, and stress and time dependent. Due to the absence of a stabilized soil performance model, both the rigid and flexible linear-elastic performance models were used to evaluate the stabilized soil layers. The modes of failure and critical response parameters are different for rigid and flexible pavements when analyzed using multi-layer elastic methods. Therefore, the evaluation methodology and required inputs vary for the two approaches. The rigid analysis requires the inputs of elastic modulus, flexural strength, Poisson's

ratio, degree of bonding, surface condition index at failure, and the layer thickness for the surface material. The material properties required for the surface layer in a flexible pavement evaluation include the elastic modulus, Poisson's ratio, degree of bonding, and thickness of the layer. For both evaluation approaches, the subsurface pavement layer inputs include elastic modulus, Poisson's ration, degree of bonding, and thickness of the layers.

The material inputs for the surface layer of a stabilized soil pavement can be obtained through correlations to standard test methods. Mitchell et al. (1974) determined that the unconfined compressive strength is a suitable correlating parameter for the material properties of stabilized soils. The Mechanistic-Empirical Design Guide (TRB 2004) recommends determining the elastic modulus directly from repeated-load compression test or from existing correlations between the UCS and elastic modulus of stabilized materials (Equation 9). The flexural strength can also be determined directly from third-point loading or from existing correlations relating UCS to flexural strength (Equation 10).

$$Elastic\ Modulus(psi) = 1200 \times UCS \tag{9}$$

$$Modulus\ of\ Rupture(psi) = 0.20 \times UCS \tag{10}$$

Standard values of Poisson's ratio and degree of bonding can be used for stabilized materials. The values used throughout this investigation were 0.20 and 1.0, respectively. The thickness of the stabilized layer should be recorded during field characterization. The stiffness input for the subsurface layers can be determined using the DCP and established correlations relating DCP index to CBR (Equations 5–7) and CBR to elastic modulus as shown in Equation 11 (Powell et al. 1984). Common values can be used for the Poisson's ratio and degree of bonding. The thickness of intermediate layers should be noted during in situ characterization; the thickness of the subgrade need not be measured as it is assumed to be infinite in a linear-elastic analysis.

$$Elastic\ Modulus(psi) = 2552 \times CBR^{0.64} \tag{11}$$

5 Model Verification

Portland cement-stabilized test section

To validate the developed relationships, a Portland cement-stabilized test section (VTS) was constructed at the ERDC. The test section had dimensions of 60 ft × 40 ft and consisted of an 8-in. layer of SM over a compacted CH subgrade with a 10% CBR. The top 6 in. was stabilized with Portland cement, as shown in Figure 29.

The mix design was conducted in accordance with TM 5-822-14 (Joint Departments 1994). The optimum Portland cement content for 750 psi (5.17 MPa) UCS and less than 8% loss of original weight in wet-dry durability testing was determined to be 8% by weight. The target density and optimum moisture content were 125 lbm/ft^3 and 8.3%, respectively. The test section was constructed using an in-place mixing technique consisting of wetting the in-place material to optimum moisture content, blending the SM and Portland cement, and compacting using static and vibrating passes of a steel-wheeled roller. The section was allowed to cure for 7 days following construction. The VTS is shown in Figure 30 prior to testing.

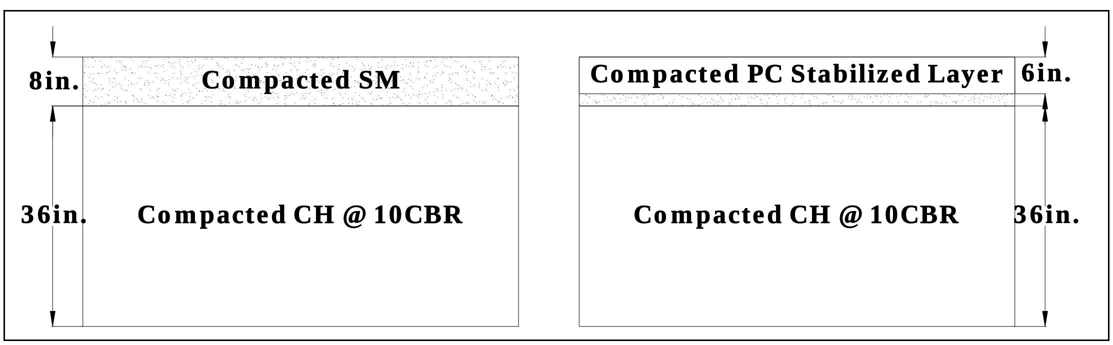

Figure 29. Cross section of verification test section before and after stabilization.

Figure 30. VTS cement-stabilized soil test section.

Material characterization

Five test locations were identified and marked every 10 ft along the centerline of the test section to enable repeated testing of the same material sample. The Clegg hammer, PFWD, and PSPA were used to evaluate the stabilized soil surface at each of the marked test locations. The DCP and SSG were not used to evaluate the VTS due to the low R^2 of the relationships developed in the previous in situ testing. In addition to the in situ measurements, samples were extracted from the pavement for laboratory testing.

Twenty-four 4-in. core samples were recovered from the test section in addition to one 18-in. × 18-in. slab. In total, fifteen core samples were tested in unconfined compression, nine core samples were tested in repeated-load compression, and three 3-in. × 3-in. × 11.25-in. beam samples were cut from the recovered slab and tested in third-point loading. The FWD testing was conducted before, and the stabilizer content testing after, extraction of the slab material.

Table 5 presents the measurements collected in situ, and Table 6 presents the standard method test results. The in situ evaluation, FWD testing, and material sampling were conducted at the end of the 7-day curing period. The UCS testing was conducted on 8-day-old samples, the flex strength and repeated load testing on 9-day-old samples, and the stabilizer content determination on samples beyond the initial 28-day curing period.

Table 5. Verification section in situ test device measurements.

Verification Test Site	Surface Thickness in.	Clegg Hammer (CIV)	DCP Index	SSG Elastic Modulus psi	PFWD Elastic Modulus psi	PSPA Elastic Modulus psi
VTS 1	7	82	__[a]	__[a]	79,000	1,183,333
VTS 2	7	85	__[a]	__[a]	102,033	976,667
VTS 3	7	83	__[a]	__[a]	99,833	806,667
VTS 4	7	83	__[a]	__[a]	96,433	1,365,000
VTS 5	7	82	__[a]	__[a]	111,633	1,380,000
AVERAGE	**7**	**83**	**__[a]**	**__[a]**	**97,787**	**1,142,333**

[a] Data not collected during verification testing.

Table 6. Verification section standard test method measurements.

Verification Test Site	UCS psi	Flex Strength psi	Repeated Load Modulus psi	FWD Modulus psi	Cement content %
VTS 1	733	__[a]	370,847	__[a]	__[a]
VTS 2	601	__[a]	238,317	__[a]	__[a]
VTS 3	547	__[a]	189,522	__[a]	__[a]
VTS 4	832	__[a]	226,127	__[a]	__[a]
VTS 5	858	__[a]	281,845	__[a]	__[a]
AVERAGE	**714**	**101**	**261,332**	**511,601**	**14**

[a] Data obtained from a single test location.

The in situ measurements collected from the VTS were input into both the correlations developed during this investigation and those obtained from literature. The strength and stiffness values predicted using the relationships are presented in Table 7. Additionally, the difference between the predicted values and the measurements obtained using the standard test methods are presented in Table 7.

Table 7. In situ testing device correlations with standard test methods.

Correlation	Material Property	Predicted Value	Variance from Actual Value
Clegg - UCS	UCS (psi)	877	163
SSG - UCS	UCS (psi)	__[a]	__[a]
PFWD - UCS	UCS (psi)	881	167
PSPA - UCS	UCS (psi)	850	136
Okamoto et al.	UCS (psi)	392	-322
Freeman et al.	UCS (psi)	752	38
Clegg - R	Modulus of rupture (psi)	115	14
SSG - R	Modulus of rupture (psi)	__[a]	__[a]
PFWD - R	Modulus of rupture (psi)	161	60
PSPA - R	Modulus of rupture (psi)	155	54
Bell	Modulus of rupture (psi)	137	36
Clegg - FWD	FWD elastic modulus (psi)	266,006	-245,595
SSG - FWD	FWD elastic modulus (psi)	__[a]	__[a]
PFWD - FWD	FWD elastic modulus (psi)	64,992	-446,609
PSPA - FWD	FWD elastic modulus (psi)	204,370	-307,231
Nazzal (SSG)	FWD elastic modulus (psi)	__[a]	__[a]
Nazzal (PFWD)	FWD elastic modulus (psi)	94,832	-416,769
Clegg - Cyclic E	Cyclic elastic modulus (psi)	297,612	36,280
SSG - Cyclic E	Cyclic elastic modulus (psi)	__[a]	__[a]
PFWD - Cyclic E	Cyclic elastic modulus (psi)	395,027	133,695
PSPA - Cyclic E	Cyclic elastic modulus (psi)	312,131	50,799
Hilbrich	Cyclic elastic modulus (psi)	847,040	585,708

[a] Soil stiffness gauge was not used during verification testing.

Simulated and live loading

In addition to validating the correlations between the in situ test devices and standard test methods, the test section was used to calibrate the PCASE performance prediction. A performance model for stabilized materials does not currently exist. The rigid and flexible pavement models used in PCASE were applied to the VTS to predict the performance of the unsurfaced layer under C-17 load cart trafficking. The performance predictions were made in PCASE using material inputs determined with the in situ test devices. The test section was trafficked to failure with a simulated C-17 six-wheel load cart (Figure 31) composed of one C-17 main gear section loaded to 223,560 lb. Failure was reached on the VTS after

Figure 31. C-17 load cart trafficking stabilized test section.

2016 passes of the C-17 load cart. Failure is indicated in stabilized pavement layers by the occurrence of ruts in excess of 3 in. or the presence of debris 1 in. or greater in diameter, capable of causing foreign object debris damage. The evaluation in PCASE was run using a vehicle setup identical to that shown in Figure 32.

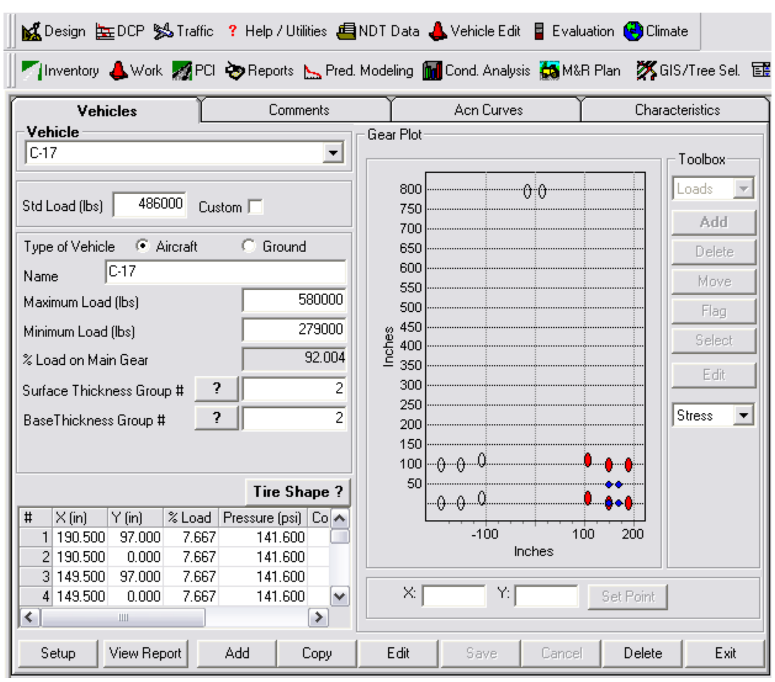

Figure 32. PCASE vehicle edit module.

Performance prediction

The correlations developed in this study and those presented in the literature were used to develop the required inputs to predict the passes-to-failure and limiting loads of the VTS using both rigid and flexible analyses in the PCASE pavement evaluation program.

For the rigid analysis, the cement-stabilized layer was evaluated as a Portland cement concrete slab. The geometry of the pavement system was maintained in the analysis. The modulus of the surface layer was input directly or estimated using Equation 9, or a standard value of 500,000 psi (TRB 2004) was used. The standard elastic modulus value was used to determine the effectiveness of the correlations predicting only flexural strength. The modulus of rupture of the layer was also directly input or was estimated using Equation 10, or a standard value of 100 psi (TRB 2004) was used. The standard modulus of rupture value was used in conjunction with predicted elastic modulus values for the rigid analysis when only elastic modulus was predicted. The modulus of the subgrade was estimated using Equation 11 based on a 10 CBR structure. For all of the PCASE analyses conducted on the VTS section, a constant subgrade modulus of 11,140 psi was used. The Poisson's ratio for the cement-stabilized surface and the subgrade were approximated at 0.20 and 0.40, respectively.

In the flexible analysis, the unsurfaced stabilized layer was evaluated as an asphalt cement concrete layer. The process used in the rigid analysis to determine surface and subgrade material property inputs was also employed for the flexible analysis. However, the modulus of rupture is not used in the flexible analysis. The PCASE performance predictions for both the rigid and flexible analyses are presented in Table 8. The difference in predicted and actual performance is shown in Figure 33.

Table 8. Verification section PCASE performance predictions.

Correlation	Elasic Modulus (psi)	Modulus of Rupture (psi)	Rigid Prediction (passes)	Flexible Prediction (passes)
Clegg - UCS	1052400	175	1	1957
SSG - UCS	—[a]	—[a]	—[a]	—[a]
PFWD - UCS	1057200	176	1	1989
PSPA - UCS	1020000	170	1	1751
Okamoto et al.	470170	78	0	111
Freeman et al.	902916	150	0	1134
Clegg - R	500,000 [b]	115	0	138
SSG - R	—[a]	—[a]	—[a]	—[a]
PFWD - R	500,000 [b]	161	1	138
PSPA - R	500,000 [b]	155	1	138
Bell	500,000 [b]	137	1	138
Clegg - FWD	266006	100 [c]	1	15
SSG - FWD	—[a]	—[a]	—[a]	—[a]
PFWD - FWD	64992	100 [c]	8	0
PSPA - FWD	204370	100 [c]	1	6
Nazzal (SSG)	—[a]	—[a]	—[a]	—[a]
Nazzal (PFWD)	94832	100 [c]	2	1
Clegg - Cyclic E	297612	100 [c]	1	22
SSG - Cyclic E	—[a]	—[a]	—[a]	—[a]
PFWD - Cyclic E	395027	100 [c]	0	60
PSPA - Cyclic E	312131	100 [c]	1	26
Hilbrich	847040	100 [c]	0	903

[a] Soil stiffness gauge was not used during verification testing.

[b] Standard value for elastic modulus of cement-stabilized materials used.

[c] Standard value for modulus of rupture of cement-stabilized materials used.

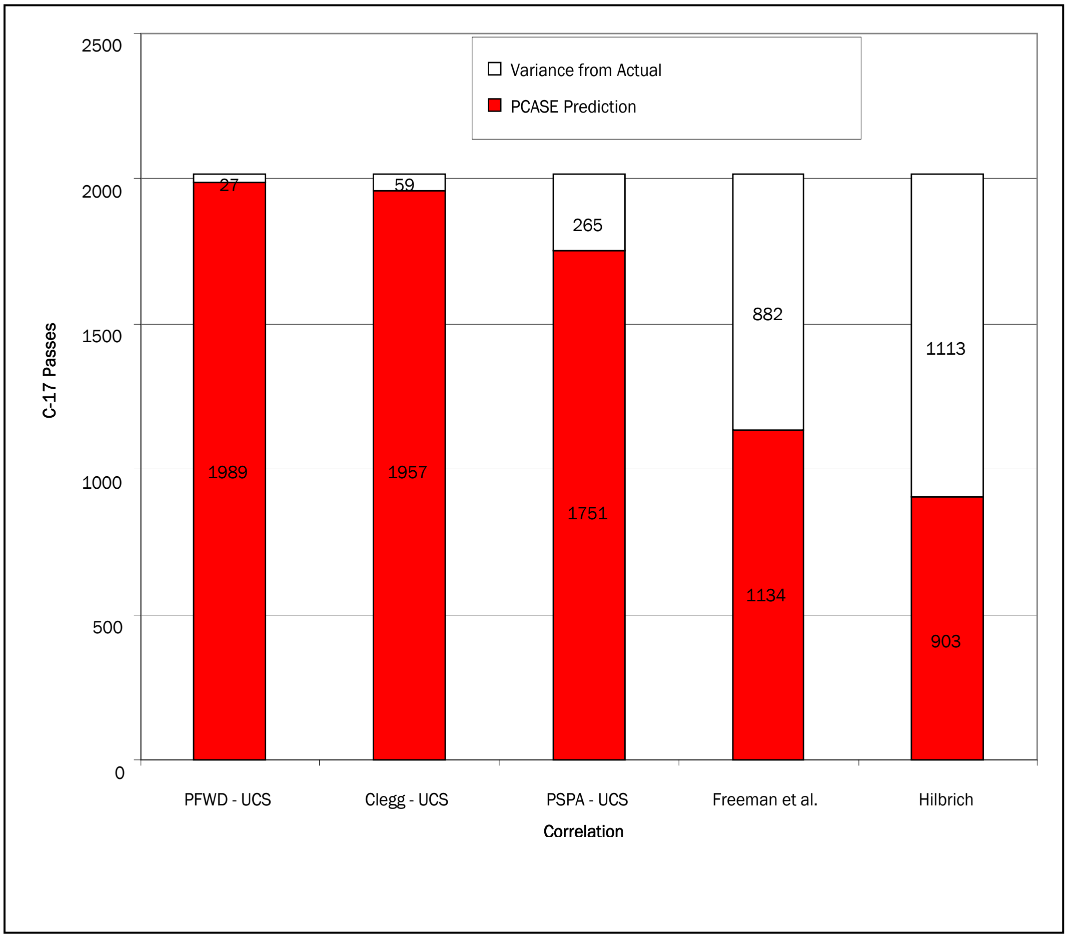

Figure 33. Variance of most accurate performance predictions from actual.

Critical findings

Five in situ test devices were evaluated to determine the feasibility of using the devices to characterize unsurfaced stabilized soil airfields. Relationships were developed between in situ test device and standard test method measurements. Three measures of effectiveness for each correlation were evaluated, including determining the coefficient of determination, root mean squared error, and deviation in performance prediction. The following are the critical findings of this investigation:

- The strongest relationship developed in this study as determined using the R^2 value was the PSPA prediction of backcalulated FWD elastic modulus. The R^2 value for this relationship was 0.53, which indicates that the relationship accounts for 53% of the variation of the predicted values compared with the observed values. The

remaining error can be attributed to variability in the pavement layer as evidenced by the differences in cement content shown in Table 4, as well as inherent variability in the test method.
- The most successful predictions of UCS were made using the Clegg hammer.
- The most successful predictions of modulus of rupture were achieved using the PSPA.
- No successful predictions of repeated-load elastic modulus were made using the in situ test devices examined in this study.
- The relationships with the least amount of error between the predicted and measured values (RMSE) were the Clegg predictions of UCS, modulus of rupture, and backcalulated FWD elastic modulus. However, the correlations are based on narrow bands of data that cannot be successfully extrapolated over the range of expected CIV values.
- The performance model inputs that yielded the closest prediction of actual performance when input into PCASE were obtained using the PFWD correlation for the determination of UCS. The model was found to be slightly conservative, underpredicting the performance of the VTS stabilized soil layer by 27 passes of the C-17 load cart.
- The presented correlations exhibit variability and should be used with caution where the performance of standard test methods is not practical.

6 Conclusions and Recommendations

Conclusions

A method for the in situ evaluation of stabilized soils does not currently exist. The DoD uses unsurfaced Portland cement-stabilized soil airfields as ALRS and also as contingency training facilities, and a method for determining the remaining operations capacity of these facilities is required. The ERDC sought to develop a method for evaluating the stabilized soil pavement layers by using in situ strength and stiffness measuring devices to develop the material property inputs for the PCASE pavement evaluation software program. The in situ measurements were correlated to standard test methods and used to predict the performance of the stabilized materials in both rigid and flexible analyses.

- No strong relationships could be developed. However, the several modest relationships could be employed in the absence of better data.
- Select in situ measurements and associated correlations can be used in PCASE to provide an estimate of the performance of a stabilized-soil pavement layer.

Soil stabilization with Portland cement is a popular and cost-effective method for improving the quality of in situ soils. The ability of the Clegg hammer, DCP, SSG, PFWD, and PSPA to accurately determine the material properties has been assessed.

- Only modest relationships were observed between the strength and stiffness values measured in situ and those values determined through standard test methods.
- Due to the proven ability of these devices to monitor stabilized materials, these technologies can be effectively employed in quality control activities.

Recommendations

The development of a stabilized soil performance model is required to accurately predict the operational capacity of stabilized soil-surfaced

airfields. Current linear elastic models can be used to provide an estimate of the performance capacity of stabilized soil pavement layers.

Due to the complex performance characteristics of stabilized materials, additional research is needed to determine the ultimate load bearing capacity, strength deterioration rate after initial cracking, influence of measurable material properties, and material durability under wheel loading of stabilized soil materials.

This research should be incorporated into the development of a finite element model that can be used to accurately predict the performance of stabilized-soil pavement layers.

References

American Society for Testing and Materials. 2006. *Annual book of ASTM standards*. West Conshohocken, PA.

Ang, A. H.-S. and W. H. Tang. 2007. *Probability concepts in engineering: Emphasis on applications in civil and environmental engineering*. 2d ed. Hoboken, NJ: John Wiley and Sons.

Bell, H. P. 2006a. *Operating the portable seismic pavement analyzer*. ERDC-GSL SR-06-9. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

_____. 2006b. *Seismic measurements of concrete strength properties*. ERDC/GSL TR-06-27. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Bush, A. J., III, and S. Alford. 1986. *Alternate launch and recovery surface test section, design, construction, and evaluation, North Field, South Carolina*. Technical Report ESL-TR-85-37. Washington, DC: Air Force Engineering and Services Center, Department of the Air Force.

Dynatest International. 2006. *Dynatest 3031 LWD light weight deflectometer; owner's manual, version 1.0.1*. Ventura, CA.

Enayatpour, S., A. J. Puppala, and H. Vasudevan. 2007. Site and geomaterial characterization (GSP 149); dynamic cone penetrometer to evaluate unconfined compressive strength of stabilized soils. http://www.ascelibrary.org/.

Freeman, R. B., T. A. Mann, L. W. Mason, C. A. Gartrell, and V. M Moore. 2008. *Quality assurance for rapid airfield construction*. ERDC/GSL TR-08-7. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Guthrie, W. S., and G. B. Reese. 2008. *Use of the heavy Clegg impact soil tester to assess rutting susceptibility of cement-treated base material under early trafficking*. 87th Annual Meeting. Washington, DC: Transportation Research Board of the National Academies.

Hadley, W. O. 1991. Material characterization and inherent variation analysis of soil-cement field cores. *Journal of the Transportation Research Board* 1295:23–36.

Heymsfield, E., W. D. Hodo, and R. E. Wahl. 2007. Development of a damage model to analyze stabilized soil layers subjected to repetitive aircraft loadings. In *Transportation Research Board 2007 annual meeting* (CD-ROM), 1–17. Washington, DC: Transportation Research Board of the National Academies.

Hilbrich, S. L., and T. Scullion. 2007. Rapid alternative for laboratory determination of resilient modulus input values on stabilized materials for AASHTO mechanistic-empirical design guide. *Journal of the Transportation Research Board* 2026: 63–69.

Humboldt Manufacturing Company. 2002. *GeoGauge (soil stiffness and modulus) user guide, version 4.5*. Norridge, IL.

Joint Departments. 1994. *Soil stabilization for pavements*. Army Technical Manual 5-822-14/Air Force Manual 32-1019. Departments of the Army, the Navy, and the Air Force.

_____. 2001a. *Pavement design for airfields*. Unified Facilities Criteria 3-260-02. Washington, DC: Departments of the Air Force, Army, and Navy.

_____. 2001b. *Airfield pavement evaluation*. Unified Facilities Criteria 3-260-03. Washington, DC: Joint Departments of the Air Force, Army, and Navy.

Lade, P. V. 2002. Instability, shear banding, and failure in granular materials. *International Journal of Solids and Structures* 39(14):3337–3357.

Lafayette Instrument Company. 2006. *Clegg manual*. Lafayette, IN.

Mitchell, J. K., P. Dzwilewski, and C. L. Monismith. 1974. *Behavior of stabilized soils under repeated loading; Report 6, A summary report with a suggested structural pavement design procedure*. Contract Report 3-145. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Nazzal, M. D. 2003. Field evaluation of in-situ test technology for QC/QA procedures during construction of pavement layers and embankments. MS thesis, Louisiana State Univ.

Okamoto, P. A., B. T. Bock, and P. J. Nussbaum. 1991. Nondestructive tests for determining compressive strength of cement-stabilized soils. *Journal of the Transportation Research Board* 1295:1–8.

Parsons, R. L and J. P. Milburn. *Engineering behavior of stabilized soils. Journal of the Transportation Research Board* 1837:20–29.

Powell, W. D., J. F. Potter, H. C. Mayhew, and M. E. Nunn. 1984. *The structural design of bituminous roads*. TRRL Laboratory Report 1132. Crowthorne, England: Transportation and Road Research Laboratory.

Tingle, J. S., S. L. Larson, C. A. Weiss, J. K. Newman, J. F. Peters, B. Tardy, and E. J. Berney. 2004. *Constitutive analysis of nontraditional stabilization additives*. ERDC/GSL TR-04-5. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Transportation Research Board of the National Academies. 1999. *Measuring in situ mechanical properties of pavement subgrade soils*. NCHRP Synthesis No. 278. Washington, DC: National Cooperative Highway Research Program.

_____. 2004. *Guide for mechanistic-empirical design of new and rehabilitated pavement structures*. NCHRP 1-37A. Washington, DC: National Cooperative Highway Research Program.

Wang, Mian-Chang. Stresses and Deflections in Cement-stabilized Soil Pavements. Dissertation. University of California, Berkley, 1968.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
July 2008	Final report	

4. TITLE AND SUBTITLE

In Situ Evaluation of Unsurfaced Portland Cement-Stabilized Soil Airfields

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Jonathon R. Griffin and Jeb S. Tingle

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Geotechnical and Structures Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/GSL TR-09-20

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Headquarters, Air Force Civil Engineer Support Agency
139 Barnes Avenue, Suite 1
Tyndall Air Force Base, FL 32403-5319

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The U.S. Army Engineer Research and Development Center (ERDC) was tasked to develop a method for the in situ evaluation of unsurfaced Portland cement-stabilized soil airfields. The ability of portable in situ strength and stiffness measuring devices to determine the material properties of stabilized soils was investigated using the Clegg hammer, dynamic cone penetrometer, soil stiffness gauge, portable falling-weight deflectometer, and portable seismic property analyzer. Regression and correlation analyses were performed to develop relationships between the in situ test device measurements and the unconfined compressive strength, modulus of rupture, repeated-load elastic modulus, and falling-weight deflectometer backcalculated elastic modulus of representative materials. Relationships proposed in previous studies were found ineffective, and a precise relationship for the determination of cement-stabilized soil material properties was not discovered. As a result of this study, it has been determined that further research is required for the development of an accurate cement-stabilized soil performance model.

15. SUBJECT TERMS

	Material characterization	
Full-scale testing	Performance prediction	Stabilized soil
In situ evaluation	Simulated live aircraft loading	Unsurfaced airfield

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		57	